Multiferroic oxides-based flash-memory and spin-field-effect transistor

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We propose a modified spin-field-effect transistor fabricated in a two dimensional electron gas (2DEG) formed at the surface of multiferroic oxides with a transverse helical magnetic order. The topology of the oxide local magnetic moments induces a resonant momentum-dependent effective spin-orbit interaction acting on 2DEG. We show that spin polarization dephasing is strongly suppressed which is crucial for functionality. The carrier spin precession phase depend linearly on the magnetic spiral helicity. The latter is electrically controllable by virtue of the magento-electric effect. We also suggest a flash-memory device based on this structure.

Spin-based electronics, or spintronics has been a growing area of research with a number of promising applications [1]. A widely discussed device is the spin-field-effect transistor (spin-FET) proposed by Datta and Das [2]. In this device, electrons with a definite spin orientation leaving a ferromagnetic source traverse a semiconductor-based 2DEG with a gate-controlled Rashba [3] spin-orbit interaction (SOI) and arrive at a ferromagnetic drain. The *on* and *off* states are distinguished by π phase difference in spin precession motion (due to SOI). A crucial point in this device is the wave-vector ($\boldsymbol{k}$)-dependence of the Rashba SOI: the momentum scattering reorients the direction of the precession axis resulting a random effective magnetic field. This leads to an average spin dephasing and limits the practical functionality of the Datta-Das FET to the (quasi) ballistic regime. For systems with a Dresselhaus [4] SOI in addition to the Rashba SOI, another type of spin FET is proposed in Ref.[5, 6] when these two types of SOIs are exactly balanced: The relaxation of spins oriented along the [110] axis is totally suppressed; non-magnetic scatterer cannot induce a spin flip enhancing thus the spin-coherence time, as demonstrated recently [7]. The disadvantage of such a resonant spin-FET is obviously that the current during the off state is not zero but approximately one-half of the on-current which underlies the view [8] that the present versions of spin-FET are not likely to be competitive with their electronic counterparts.

Recently, 2DEG is experimentally realized at the interface of insulating oxides [9, 10]. Lateral confinement and patterning [11] allowed the demonstration of nanometer-sized tunnel junctions and field-effect transistors [12], which opens the way for oxide-based Nanoelectronics [11]. In this letter we show that utilizing the 2DEG formed at the surface of multiferroic oxides (Fig.1), the original Datta-Das device is operational even in the non-ballistic regime. Due to the topological structure of the local magnetic moment at the multiferroic interface (Fig.1), a traveling electron experiences an effective SOI that linearly depends on the carriers wave vector and on the helicity of the oxide's magnetic order [13]. Such an effective SOI is in a complete analogy to the semiconductor case where the Rashba SOI and Dresselhaus SOI have equal strengths. Therefore, no decay of spin polarization coherence occurs during a momentum-dependent scattering. On the other hand, as shown experimentally, the helicity associated with the spin spiral structure of multiferroics is electrically [14] and/or magnetically [15] controllable based on the magneto-electric coupling [16], and so is the resulting phase difference in spin precessional motion when traversing the 2DEG.

The proposal is sketched in Fig.1, a 2DEG is realized at the surfaces of a spiral multiferroic oxide such as the ab plane of $TbMnO_3$ [17]. The local magnetic moments at the multiferroic surface reads $\boldsymbol{M}_r = M_0\boldsymbol{n}_r$, where $\boldsymbol{n}_r = (\sin(\boldsymbol{q}_m \cdot \boldsymbol{r}), \cos(\boldsymbol{q}_m \cdot \boldsymbol{r}), 0)$ with $\boldsymbol{q}_m = (q, 0, 0)$ being the spin-wave vector of the spiral. The oxide local spin dynamics is much slower than that of the carriers in the 2DEG, so one may assume at low-temperatures that the oxide local magnetic moments are classical and static. A conducting carrier is subject to an effective internal magnetic field generated by the magnetic spiral in the embedding medium [18, 19, 20]. This results in a nonlocal vector potential. However, the energy contribution from the vector potential is much smaller than any relevant energy scale in the system and can be neglected [13]. Thus, for the system Hamiltonian we employ the

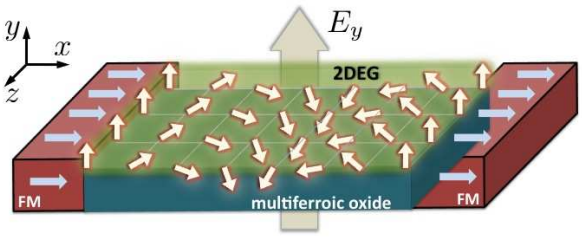

FIG. 1: (Color online) A schematics of proposed spin-FET device. Two ferromagnetic contacts are magnetized in the x-direction. The spiral plane of multiferroic oxide is perpendicular to the device, and the spin helicity is gate-controlled (E_z).

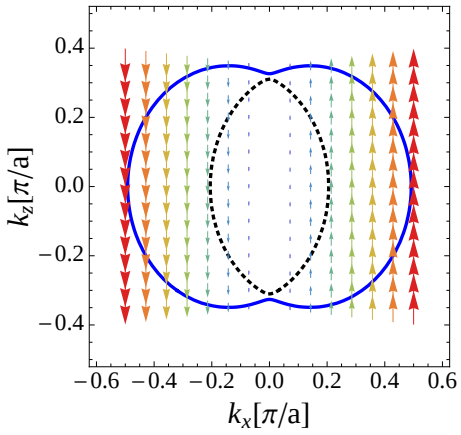

FIG. 2: (Color online) The arrows show the momentum-dependent magnetic fields induced by the effective spin-orbit interaction, $qk_x\sigma_z$. Also shown are the energy dispersions $E_+(\boldsymbol{k})$ (dotted curve) and $E_-(\boldsymbol{k})$ (solid curve) with $E = \frac{\hbar^2}{2ma^2}$, $J/E = 0.05$. The spiral wave vector is $q = 2\pi/7a$.

form

$$H = \frac{1}{2m}\boldsymbol{P}^2 + J\boldsymbol{n}_r \cdot \boldsymbol{\sigma} \tag{1}$$

where m is the effective electron mass, $J\boldsymbol{n}_r$ is the exchange field [16, 21], J is the coupling strength, $\mathbf{P}$ is the momentum operator, and $\boldsymbol{\sigma}$ is the vector of the Pauli matrices.

Using the local gauge transformation in the spin space $U_g = e^{i\theta_r\sigma_z/2}$ one achieves $U_g^\dagger(J\boldsymbol{n}_r \cdot \boldsymbol{\sigma})U_g = J\tilde{\sigma}_y$ (transformed quantities are labeled by a tilde). This corresponds to a rotation of the local quantization axis as to align with $\boldsymbol{n}_r$ at each site. Note, $\sigma_z = \tilde{\sigma}_z$ because $[U_g, \sigma_z] = 0$. As a result of the gauge transformation, an additional gauge field $\boldsymbol{A}_g = -i\hbar U_g^\dagger \nabla_{\boldsymbol{r}} U_g = \hbar\tilde{\sigma}_z\boldsymbol{q}_m/2$ is introduced in the transformed kinetic energy [22]. The gauge field $\boldsymbol{A}_g$ depends only on the geometry of the local magnetization at the oxide [13]. Since $\boldsymbol{A}_g \propto \boldsymbol{q}_m$ it can be changed electrically because $\boldsymbol{q}_m$ is gate-tunable, e.g. in the way sketched in fig.1. The transformed single-particle Hamiltonian of the 2DEG reads

$$\tilde{H} = \frac{1}{2m}(\boldsymbol{P} + \boldsymbol{A}_g)^2 + J\tilde{\sigma}_y. \tag{2}$$

The parameters entering this Hamiltonian have the following realistic values for a 2DEG at oxides interfaces: the lattice constant $a = 5\mathring{A}$ and the effective mass $m/m_e = 10$ with m_e being the free-electron mass [10]. Removing a uniform energy displacement $\Delta E = \hbar^2q^2/8m$, we rewrite the Hamiltonian in the form

$$\tilde{H} = \frac{\hbar^2}{2m}(k_x^2 + k_z^2 + qk_x\tilde{\sigma}_z) + J\tilde{\sigma}_y \tag{3}$$

From this relation we infer that the influence of the spiral multiferroic interface on the 2DEG is subsumed in an effective SOI that depends linearly on $\boldsymbol{q}_m$ and $\boldsymbol{k}$ (for $q \to 0$, i.e. for collinear spin case this SOI diminishes). The $\boldsymbol{k}$-dependence is analogous to semiconductor-based 2DEG with the Rashba and Dresselhause SOI [5, 6] being equal, in which case the effective magnetic field is oriented along the [110] axis irrespective of $\boldsymbol{k}$ and the spin traverses the [110] channel without flipping. In our multiferroic oxide system, the helical spin order lead to a zero average spin relaxation in xy-plane, the electron spin relaxation will be associated only with the electron diffusion along the z direction [23]. As shown in Fig.2, the resonant effective SOI strongly suppresses the spin dephasing along the z-axis.

The eigenstates of $\tilde{H}$ read

$$|\psi_+\rangle = e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\begin{pmatrix}\cos\frac{\phi}{2}\\ i\sin\frac{\phi}{2}\end{pmatrix},\ |\psi_-\rangle = e^{i\boldsymbol{k}\cdot\boldsymbol{r}}\begin{pmatrix}i\sin\frac{\phi}{2}\\ \cos\frac{\phi}{2}\end{pmatrix} \tag{4}$$

where

$$\cot\phi = \frac{\hbar^2qk_x}{2mJ},\ \ \cos\phi = \frac{qk_x}{\sqrt{(2mJ/\hbar^2)^2 + (qk_x)^2}}. \tag{5}$$

The eigenenergies are

$$E_\pm(\boldsymbol{k}) = \frac{\hbar^2\boldsymbol{k}^2}{2m} \pm \frac{\hbar^2qk_x}{2m}\sqrt{1 + (\frac{2mJ}{\hbar^2qk_x})^2}. \tag{6}$$

Because of the effective spin-orbit coupling, the dispersions (6) are not parabolic but anisotropic. The $\hat{x}$ and $\hat{z}$ are the symmetry axes (cf. Fig.2). Although the spin states Eq.(4) are not independent of $\bar{\boldsymbol{k}}$, we still have no decay of the spin-polarization coherence along $\hat{z}$ (in absence of magnetic scattering) just as in the case without magnetic field in Ref.[5, 6]. More importantly, as evidenced by spin-polarized neutron scattering experiments [14], one can change the helicity of the spiral magnetic order by applying a small ($\sim 1kV/cm$) transverse electric field. By doing so we achieve a gate-tunable phase difference $\Delta\theta$ in spin procession when the electron traverses

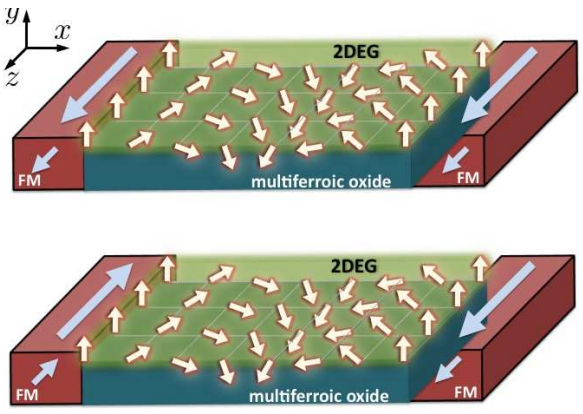

FIG. 3: (Color online) A proposal for a flash memory device. Different memory states are stored as the relative orientations of the ferromagnetic source and drain.

the 2DEG, where

$$\Delta\theta = (k_x^+ - k_x^-)L = qL. \quad (7)$$

Here L is the length of SOI active region, the double sign $\pm$ corresponds to the spin-up and spin-down branches. Note, in the above relation, we take an approximation of relatively weak exchange interaction in a high electron mobility transistor (*i.e.*, $J \ll \hbar^2 q k_x/2m$). In multiferroic oxide, a period of the spiral spin modulation is several lattice constant a, so L is on the nanometer scale.

Because the effective SOI always satisfies the resonance condition in our case another device, a flash memory is realizable as shown in Fig.3 in a similar manner as proposal in Ref.[6]. The "0" and "1" states are indicated by the relative orientation of the magnetization of the ferromagnetic source and drain.

In summary, a multiferroic oxide-based 2DEG can be utilized as a nanometer-scale, decoherence-suppressed spin field-effect transistor and as a nanometer flash-memory device.

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